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INVESTIGATIONS OF THE MEASUREMENT OF NOISE

Final Report, Contract OEMsr 1478

Developed under the supervision of the National Defense Research Committee, Office of Scientific Research and Development.

APPROVED BY
NDRC DIVISION 13

UNIVERSITY OF PENNSYLVANIA
Moore School of Electrical Engineering
PHILADELPHIA, PENNSYLVANIA

October 31, 1945

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Investigations of the Measurement of Noise

Submitted to Division 13, NDRC,
October 31, 1945.

Report of Work on Contract No. OEMsr-1478, Symbol Nos. 6050 and 6443

between

The Office of Scientific Research and Development
National Defense Research Committee
Washington, D. C.

and

University of Pennsylvania
Moore School of Electrical Engineering
Philadelphia, Pa.

Within the University of Pennsylvania the work under Contract No. OEMsr-1478 is called Project PB; the Navy designation of this project is NS 368.

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Investigations of the Measurement of Noise

Submitted to Division 13, NDRC,
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SECTION I.

Introduction

The subject of contract OEMsr-1478 is stated as follows:

> "To conduct miscellaneous studies and investigations involving radio interference phenomena including development of standards for measurements and measurement techniques, comparison of various types of noise meters and construction of a standard noise meter."

The contract was originally signed for the period June 4, 1945 to August 31, 1945. The contract was then extended to September 30, 1945; there was a final extension to October 31, 1945.

During September and October discussions with the Navy Bureau of Ships have led to the preparation of a contract now in the process of development between the University of Pennsylvania and the Navy Bureau of Ships to begin November 1, 1945. This contract has been prepared to carry the work until June 30, 1946; the new contract is No. NObs 25397.

Earlier work on this project was reported in BIMONTHLY REPORT No.1, August 4, 1945. Since that report was prepared, it was determined that the OSRD was to terminate this contract on or before October 31, 1945. Professor Dalziel immediately took up the question of extending the work by means of another contract with one of the Services, with the results outlined above.

In addition to the Bureau of Ships of the U.S. Navy, the Radio and Radar Division of the U.S. Army Air Force and the Signal Corps have indicated their interest in the continuation of the work being undertaken at the University of Pennsylvania. It is understood that the new contract with the U.S. Navy will permit the correlation of these several groups, so that they can receive reports and take part in conferences related to the work of the Project.

The need for investigation of radio noise measurements arises from the fact that measurements, using noise meters that are now available, show anomalous discrepancies.

It is reported that various instruments having been calibrated with sine wave signals read differently to as great an extent as 1000 to 1 when they are presumably reading the field intensity from the same

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noise source. With the same meter very different results are frequently obtained, when readings are taken on two frequency bands in the region of their overlap. In each case the degree of the discrepancy is reported to be different for different noise sources. We understand that these discrepancies are greater when radiated noise is being observed than when direct conducted noise is being observed.

It was reported in the BIMONTHLY REPORT No. 1 that research engineers of the University of Pennsylvania were carrying out conferences with members of the Armed Services who have been working on problems related to the work under contract OEMsr-1478; that requests were submitted for signal generating equipment and noise meters; and that each engineer was investigating a specific problem having to do with the testing of noise meters or the design of a new noise meter. For details of these matters please refer to BIMONTHLY REPORT No. 1.

During August and September some of the instruments requested during June and July were received and additional equipment has come in since October 1. Instruction manuals were obtained for many of these instruments and these devices were given preliminary tests to be sure that they were in working order. Unfortunately, neither the Ferris Noise Meter, the Stoddart Noise Meter, nor the necessary Signal Generators which were expected in August have as yet arrived. Plans for a screened room were completed and materials were ordered. At the request of OSRD the construction of the screened room was postponed in order that no unnecessary expenses might be incurred, if the contract were to be terminated suddenly. When it became clear that the Navy was interested in having the project continued, work on the screened room was begun (October 1, 1945); the room is now nearly completed.

Since it was not possible to proceed with an experimental program during the first several months, certain topics were chosen for investigation by the engineers. These investigations involved a search of the literature, examination of reports on the performance of noise meters, and the preparation of certain analyses. The analyses were necessarily incomplete because the apparatus was not available for making the necessary experimental observations. Summaries are given in Appendices A, B, C and D. As these analyses proceeded it became clear that a convenient division of the problem into three parts could be made as follows:

1. A critical analysis - both experimental and theoretical - of present noise meter circuits (including pickup devices) and their responses to various types of noise. This involves also a study of the reported discrepancies among various noise meters used with the same source, and the same noise meter used at different times with an allegedly constant source.

2. The careful preparation of specifications for satisfactory noise meter performance. This includes the crystallization of the concept of noise and the adaptation of the indicator of the noise meter to indicate a measure of that noise. It also includes the definite and unambiguous specification of the input coupling devices and their use.

3. The design and construction of a noise meter (or noise meters) to satisfy the specifications determined by the procedure mentioned in 2. above.

The sections which follow are concerned with these three topics - and particularly with the first two. The design and construction of a noise meter depends essentially on the results of the critical analysis of the present noise meter (item 1.) and upon the preparation of specifications for a noise meter (item 2.) Therefore, the next two sections of this report are devoted to items 1. and 2. above.

SECTION II.

Analysis of Present Noise Meters

As stated in Section I. the data recorded by the use of present day noise meters have indicated important and unexplained discrepancies. Owing to a lack of equipment it has not been possible to perform experiments on this project to investigate this important aspect of the general problem. Nevertheless, possible causes of these discrepancies have been mentioned by other workers and have arisen also from the analyses of the engineers on this project.

A possible cause of these discrepancies is the variability of pickup devices and methods of using them. Thus a theoretical analysis+) indicates that the use of a dipole for fields close to the source may lead to unpredictable errors in measurement; and that a loop may be preferable in such circumstances. It is also clear that, regardless of what pickup method is used, the presence of other electrically conducting materials in the vicinity of the noise measuring setup may cause errors. Representatives of the Navy have suggested the possibility of using a "Condenser Pickup"; this deserves a careful experimental investigation to determine among other questions whether it is possible to obtain adequate sensitivity.

+) Refer to Appendix A of this report.

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Investigators of the Army Air Corps have suggested that the convertor in a noise meter, operating over a wide range of amplitudes, may be a source of anomalous results. Accordingly, a preliminary analysis of the square-law mixer[+]) has been made. This indicates that if first order image rejection is satisfactory, the intermodulation terms of the first order are likely to be of small importance. A detailed analysis by means of a Fourier expansion is required in order to investigate the effects of higher order terms. The experimental analysis of this problem will involve a study of image rejection in present meters, particularly at high frequencies. First tests in this laboratory of a Measurements Laboratory noise meter indicate that this problem is well worth investigating, particularly at high frequencies. It will be necessary also to perform experiments on converter noise.

In a noise meter, the detector and indicating device requires extremely careful investigations. Specifications so far set up for such apparatus are definite, but the effectiveness of the devices so specified for measuring noise is questionable. This results in part from the wide variations in the peak values and wave forms of the voltages fed to the device. Some of the points related to this problem are discussed in Appendix C. The entire problem of detectors and indicating devices is closely related to the definition of noise which is included in Section III. of this report.

Specifications have been suggested for the width of the pass band for noise meters. However, it may be important to test the effect of phase shift, which will presumably produce different effects on different types of noise with a given band-pass circuit. This is an extensive experimental problem, for which no reasonable analytical method is available. Examples which can be readily computed are so idealized that their results are of doubtful value. A simple experimental procedure would be to test the response of the band-pass circuit for pulses, steps and random noise.

All noise meters have a limited dynamic range. It is quite probable that a very important error of measurement may be produced by the overloading of some component in the noise meter by some kinds of noise - such as sharp pulses with low repetition rate. When noise meters are assembled on this project, tests of this effect will be made.

[+]) See Appendix B.

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SECTION III.

Determination of Specifications of Noise Motor Performance

In order to determine specifications for a noise motor, some consideration should be given to each of the following items:

1. Definition of Noise
2. Interfering Effect of Noise
3. Present Noise Motor Specifications
4. Methods of Coupling a Noise Motor to a Source of Noise.

1. Definition of Noise

Noise may be defined as any undesired signal having a wide frequency spectrum. Two general types of noise are usually distinguished for the purpose of analysis: a. random or fluctuation noise, b. pulse noise.

Man made noise may be a combination of both types. Pulse noise is defined as individual pulses discretly separated in time. These signals are easier to study both theoretically and experimentally and they are easily defined.

"Random" noise may be defined as a large number of individual pulses which are superimposed. They may be of random amplitude and random phase or constant amplitude and random phase. This type of noise has also been referred to as "fluctuation" noise, "white" noise or "hiss" noise. White noise is in general any noise where the energy is uniformly distributed in the frequency spectrum.

Noise has been distinguished as to whether the individual pulses were overlapping or non-overlapping.+) Using this distinction, experimental and theoretical results showed that the peak value is proportional to bandwidth for non-overlapping pulses, and proportional to the square root of bandwidth for overlapping pulses.

The conceptions of random noise and impulse noise are not sufficiently specific to distinguish different types of noise, when it is considered that the measurement of noise must be applicable

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+) Landon, V. D. "Noise Characteristics", Proc. I.R.E., 24, Nov.1936.

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to wide band reception such as that occurring in radar and television and again narrow band reception such as that occurring in speech or telegraph transmission. A pulse repetition rate of 100,000 per second would have the characteristics of impulse noise, when received by a radar or television receiver, but would appear more like random noise when received by a speech receiver. It is therefore necessary to be more explicit in the description of the character of the noise.

An improved system by which the character of the noise could be specified might be to specify the quantity $\frac{dN}{dE}$ - the number of peaks per unit E having a voltage amplitude E per unit time - for all values of E. Such a specification would require a curve for each noise observation rather than the usual attempt to specify the noise as a single quantity. Of course, any such distribution curve can be specified approximately by statistical quantities such as averages, root mean square deviations, etc. Even this apparently complete specification is not absolute. In some way the sharpness of the peaks must be specified. One way of doing this is to analyze the frequency distribution although this analysis may be both complicated and confusing if the pulse repetition rate is random in character. It may be noted that for pulses short in duration compared with the period of the highest modulating frequency receivable the peak value of the wave train produced by the pulse passing through the receiver filter is proportional to the energy content of the original pulse. It is anticipated that practically all noise pulses will fall within this limitation.

2. Interfering Effect of Noise.

The chief reason for measuring noise is to state definite limits which will prevent satisfactory communication by one means or another. However, the interference to such communication depends upon certain psychological characteristics of individuals who are using the communications equipment. Thus, inevitably, certain subjective criteria related to the interfering effect of noise have been incorporated into the criteria for designing noise meters.

Thus the effects of noise on the following should be considered:

a. Telegraphic Signals

b. Speech (Telephone and Radio)

c. Television Signals

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d. Radar Signals.

In the case of speech there are two types of noise to be considered. (1) Low level noise. Here speech is understandable but the effect of the noise is one of irritation and fatigue. This is only of concern where the signals are being received for long periods of time. (2) High level noise. In this case the intelligibility is of importance. This problem has been under investigation at Harvard University and will soon be reported.

There is a conflict between the natural desire to design a noise meter which will measure certain specific physical quantities and the necessity for designing a noise meter that will be useful for indicating which noises produce the greatest interference. It appears impossible to design one noise meter which will completely satisfy both these requirements. Therefore, it will be important to consider both aspects and to note clearly in the development of a noise meter precisely how much attention is being paid to each of them.

3. Present Noise Meter Specifications

With a device of limited bandwidth it is necessary to specify whether the indicator reads peak, average or instantaneous (such as is obtained with a cathode ray oscillograph) voltage. In general it is necessary to read more than one of these quantities to specify accurately the interference effect. The present "standard" attempts to accomplish this result by choosing appropriate time constants for an intrinsically peak reading indicator.

Recommendations for noise meters in the broadcast band have been drawn up by the Joint Coordination Committee on Radio Reception of the Edison Electric Institute, National Electrical Manufacturers Association, and Radio Manufacturers Association. These are outlined below.

"Bandwidth. The bandwidth of equipment operating in a certain frequency region should be the same as that of typical equipment operating in that region.

"Time Constant of Meter Circuit. The electrical detecting circuit should have a time constant of 10 milliseconds on charge and 600 milliseconds on discharge.

"Indicating Meter. The meter should have equal increments of deflection for equal increments of direct current. The time constant should be between 200 and 400 milliseconds. (This requirement minimizes the effect of the time constants of the indicating meter on the reading.)

The meter should have a two decade logarithmic scale, the characteristic being obtained in the circuit of the meter.

"Input Voltage Range. The device should be operable with inputs from 10 microvolts to 100,000 microvolts and should handle a peak sine wave input of 10 volts with negligible distortion.

"Automatic Volume Control. A.V.C. may be used to obtain a logarithmic response. The time constant of the AVC circuit should be 200 milliseconds."

It should be emphasized that a meter built according to these recommendations does not necessarily read interference value. Nor would the reading indicate the type of noise present except possibly to indicate in a general way its spread over the band. On pulse type noise such a meter would tend to read peak value on high repetition rates and something less than peak value on low repetition rates. The problem of pulse distortion in the filters must be studied thoroughly before it will be known just what readings are obtained with the various types of noise signals.

In the case of signals where the ratio of peak to average is large the time constant in the A.V.C. circuit may result in inaccurate readings. The maximum value of this ratio which may be handled by the noise meter without distortion due to overloading and other nonlinear circuit effects must also be analyzed.

In the superheterodyne circuit such as is generally used in present noise meters a simple specification of bandwidth is not necessarily unique. There are the bandwidths of the radio-frequency amplifier and of the intermediate amplifier. Usually the i.f. amplifier is much more sharply tuned than the r.f. amplifier, hence the former largely determines the overall bandwidth of the meter. However, the bandwidth of the r.f. amplifier plays a part in determining the image frequency response of the receiver and cross-modulation effects which may be present.

A further difficulty with the bandwidth specification is that all devices operating in a certain frequency range do not necessarily have the same bandwidth. Hence it is difficult to meet this requirement with a single device.

A complete set of specifications should contain a specification of the method of calibrating the device. A preliminary study of various generators that might be used for this purpose is outlined in Appendix D.

4. Methods of Coupling a Noise Meter to a Source of Noise

In so far as coupling is concerned there are two types of noise to be considered: radiated and conducted. Radiated noise generally causes trouble because it is picked up by antennas of receiving devices. Conducted noise may generally be picked up inside the chassis of the device having been conducted there by power supply lines or cables which feed signals from other devices. In the case of poor shielding radiated noise may be picked up directly in the chassis.

Radiated noise may be most conveniently measured by means of some form of the conventional linear or loop antennas. The effectiveness of both types in both radiation and induction fields is now under preliminary investigation. The reaction of these antennas on the field when placed near the source (usually the case in noise measurements) will be studied later. A "capacitor" antenna for these measurements has been suggested by the Navy.

The methods of measurement should depend on the internal impedance of the source at both operating and noise voltage frequencies.

Further consideration of the general topic of coupling has not been undertaken.

SECTION IV.

Appendices

A. Antennas for Noise Meters

B. Frequency Conversion

C. Detectors of Electrical Noise

D. Calibration of the Noise Meter

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APPENDIX A.

Antennas for Noise Meters

The following discussion is divided into two parts. In the first the effectiveness of the dipole and loop antenna in the radiation field is considered. In the second approximate formulas are given for the ratio of voltages induced in these two types of antennas when placed at the same point in the induction field, when the dimensions of both are small compared to one half the wavelength, and where the fields are set up by (a) an elementary electric dipole and (b) an elementary magnetic dipole. No consideration of the condenser antenna is made in this section. M.K.S. units are used throughout this discussion.

Part I - Antennas in the Radiation Field

It can be shown[1] that the circuit of a receiving antenna may be represented by the following equivalent circuit:

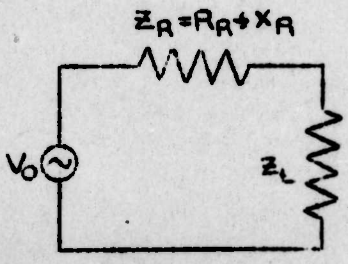

Fig. 1

Z_R is the impedance of the receiving antenna when it is driven.

Z_L is the load impedance across the terminals of the antenna.

V_0 is the open-circuit voltage across the terminals of the antenna.

This equivalent circuit will be used to find the voltage developed across the load impedance as a function of frequency for several different receiving antennas. The following assumptions are made in all the succeeding work.

1. The receiving antenna is in the radiation zone of some transmitting antenna, i.e. at a distance much greater than $\frac{\lambda}{2\pi}$ from the transmitting antenna.

2. The receiving antenna is oriented so that maximum voltage is induced in the antenna by the distant transmitting antenna.

3. The internal or ohmic resistance and the internal reactance are small compared to the radiation resistance and external reactance of the antenna.

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4. The grid circuit impedance (R_G) of the first tube is fixed at 20,000 ohms pure resistance and is independent of frequency.

5. The antenna is in a free field.

Under these assumptions the voltage developed across the load impedance of an antenna will be calculated for three cases: 1. a half wave dipole tuned to self resonance, 2. a dipole short compared to the wave length, and 3. a loop of radius less than $\frac{\lambda}{4\pi}$.

1. A half wave dipole tuned to self resonance.

The ratio of antenna length to antenna radius will first be assumed to be very much greater than one. The half wave dipole will actually be slightly less than a half wave length in order that the reactive component of the radiation impedance may be zero. Under those conditions it may be shown that the resistive component of the radiation impedance is 73.13 ohms. This resistance will, of course, be constant with frequency. It can easily be shown that for a fixed Z_R the maximum voltage will be developed across R_G when it is conjugate matched to Z_R. For an ideal match, the half wave dipole should be coupled to R_G by a "perfect" transformer with a turn ratio of $\sqrt{\frac{R_G}{R_R}}$.

The voltage developed across R_G will then be $V_G = \frac{V_O}{2}\sqrt{\frac{R_G}{R_R}}$

V_O has a value of $\frac{\lambda E}{\pi}$, hence $V_G = \frac{\lambda E}{2\pi}\sqrt{\frac{R_G}{R_R}}$, (where E is the electric field intensity in volts per meter), which varies inversely as the frequency. The magnitude of V_G at the highest frequency (150 mc) of a typical noise meter (Measurements Model 58) for a 1 microvolt per meter field will be about 5 microvolts.

If the thickness of the antenna is taken into consideration, then the radiation resistance of the half wave dipole will not be constant with frequency, but will be less than 73.13 ohms and will decrease with frequency. Then if R_G is matched to 73.13 ohms, a voltage greater than that calculated above will be obtained. This variation of the voltage from the expected value for an antenna diameter of 0.5 cm is plotted in Fig. 2. Over the 15 - 150 mc range of the Model 58 this variation is seen to be about 3 percent. The variation per megacycle is also seen to be greater at the higher frequencies.

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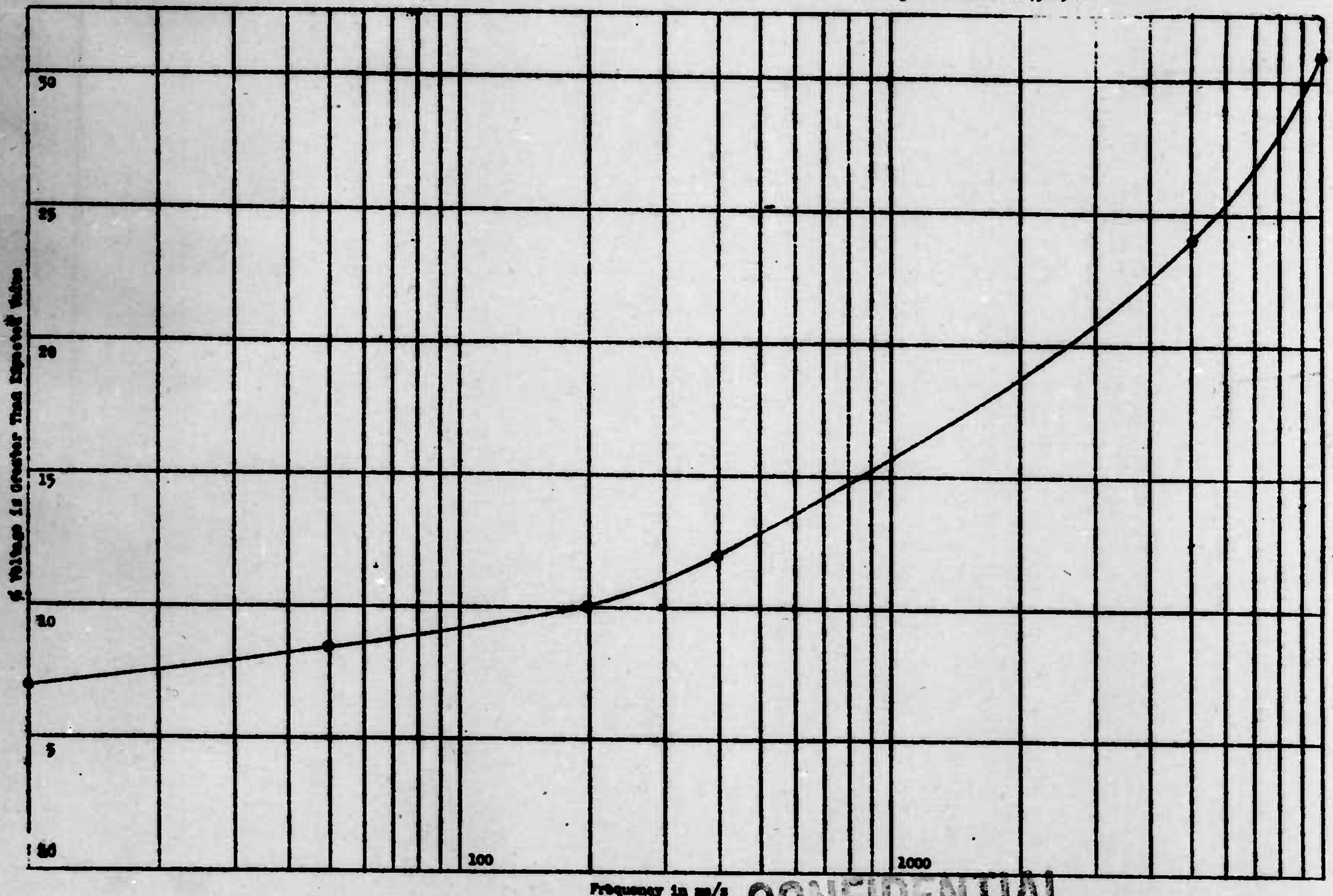
Fig. 2 - Voltage Developed Across R_g When the Diameter of the Half Wave Dipole is 0.5 cm and R_g is Matched to 73.13 ohms.



2. A dipole short compared with the wave length.

A short dipole shall be one whose length $L \leq .3\lambda$ at any frequency considered. The ratio of antenna length to radius will be assumed to be much greater than one. With these assumptions $V_0 = \frac{LE}{2}$, and if E is constant, is independent of frequency. Z_R, however, is both resistive and reactive and is a complicated function of frequency. The reactive component is capacitive and of the order of several thousand ohms, for an antenna whose length is of the order of $.3\lambda$. X_R decreases and R_R increases with increasing length and increasing frequency within the range. It will be assumed that X_R may be tuned out by varying the coupling network from the antenna to the first tube. The variation in R_R with frequency may make it impossible to match R_G to R_R at all frequencies. For example consider a short dipole 60 cms. long being used from 15 - 150 mc. The variation of R_R with frequency is shown in Fig. 3. If R_G is matched to R_R at 150 mc, then the voltage (V_G) across R_G will vary with frequency, as shown in Fig. 4. V_G for a 1 microvolt/meter field at 150 mc. is $\frac{LE}{4}\sqrt{\frac{R_G}{R_{R_{150}}}}$, which is about 2.5 microvolts. If the dipole has a finite radius, the above results will still be true to a very good approximation. The possibility of intentionally mismatching the short dipole will now be considered. The mismatch would be made so that the impedance looking into the transformer from the antenna is ten times the maximum radiation resistance. V_G would then be practically independent of the radiation resistance. V_G would still be .58 of the voltage obtained when matched and would be independent of frequency.

3. A loop of radius less than $\lambda/4\pi$.

In addition to the previous assumptions the following will be made: There are no standing waves on the loop; the streamlines of current through the conductor of the loop are parallel to the axis of the conductor; the streamlines of current are uniformly distributed across the cross-section of the conductor of the loop; the electromagnetic field throughout the loop is in phase; the effect of terminal connections is negligible.

The voltage induced in the loop is given by

$$V = 2.5 \times 10^{-5} f R_0^2 NH \text{ volts,}$$

where R_0 is the radius of the loop in meters, H is the magnetic field intensity in amperes per meter, and N is the number of turns. For a single turn loop the radiation impedance Z_R is given by (2,3)

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Fig. 3 - Variation of R_R for a 60 cm Dipole

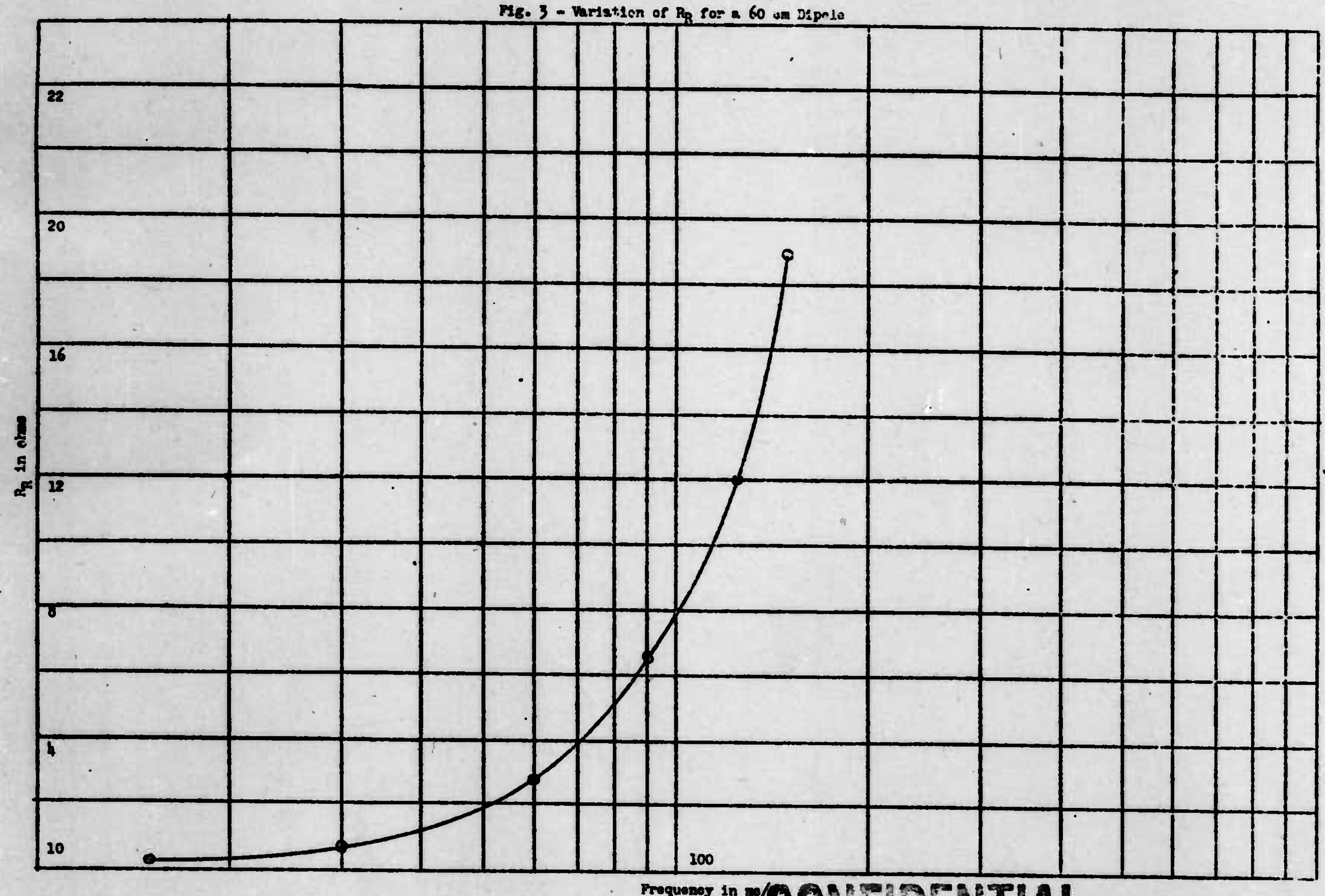

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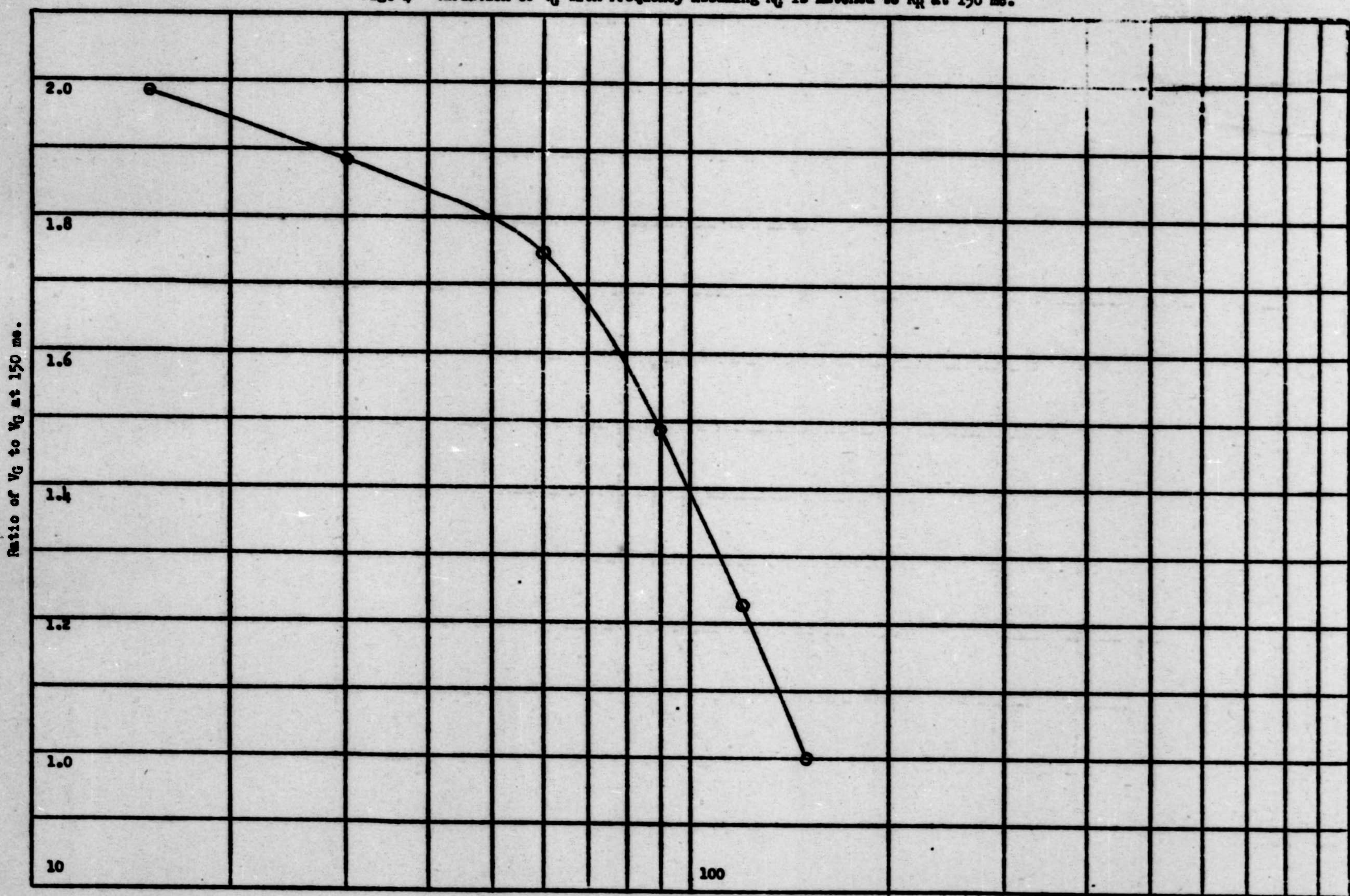
Fig. 4 - Variation of V_G with Frequency Assuming R_G is Matched to R_R at 150 mc.



$$Z_R = 3.80 \times 10^{-29} f^4 R_0^4 + j\, 7.89 \times 10^{-6} (\log_e 3.10 \times 10^3 R_0 - 1.75)\, f R_0 \text{ ohms.}$$

It should be pointed out that at low frequencies the radiation resistance is not large compared with the ohmic resistance in contradiction to assumption 3., page 11, For example the ohmic resistance of a loop made of No. 10 A.W.G. copper wire is

$$2.06 \times 10^{-2} R_0.$$

This contradiction will not affect the results that follow, however.

For a maximum frequency of 150 megacycles a single turn loop of radius .15 meters will be considered. The chart given below is obtained for frequencies as low as 150 kilocycles.

Frequency (megacycles)	150 kilocycles	1 megacycle	10 megacycles	100 megacycles
ratio of voltage (micro-volts) induced in the loop to the electric field intensity (microvolts per meter)	2.22×10^{-4}	1.47×10^{-3}	1.47×10^{-2}	1.47×10^{-1}
electric field intensity (microvolts per meter) required to induce one microvolt in the loop	4510	680	68.0	6.80

Radius of the Loop is 0.15 meters

Fig. 5

Assuming that it is required to induce at least one microvolt in the loop for satisfactory operation of the noise meter, it can be seen from the above chart that the maximum sized loop requires a high field intensity at low frequencies to induce a voltage of sufficient magnitude in the loop. At low frequencies, however, the impedance of the loop is very low and the effectiveness of the loop may be improved by proper matching or increasing the number of turns.

The value of the radiation resistance varies as the fourth power of the frequency and for the loop previously considered has a value of about 12 ohms at 150 megacycles. If the antenna is matched to the input grid, the voltage developed at this grid (V_G) will be 4 microvolts for a 1 microvolt per meter field. Further details of the problem of impedance match have not been sufficiently analyzed for presentation here.

Part II - Antennas in the Induction Field

Because the purpose of making radiated noise measurements is frequently to determine the radio interference produced by specific devices in their immediate vicinity, it has been the accepted practice to bring the antennas of noise meters very close to those devices. For instance, the proposed JAN specifications on Methods of Radio Interference Measurement requires that a distance of one foot be used. As is well known, the field at such a distance has many properties which are not described by the comparatively simple theory which applies to the field at a greater distance. It is necessary to distinguish between the field of an electric dipole and that of a magnetic one. As will be seen, there are some geometrical differences in the field as well as differences of magnitude, which do not occur for fields at remote distances.

The following assumptions are made in order to have the analysis as simple as possible:

(1) The propagation takes place in a free-field. (This assumption is close to the valid one at very short ranges. If the free-field properties are known, the effect of the ground plane can be computed.)

(2) The noise source can be represented by a simple dipole, that is, it is a simple radiator of small size.

(3) The reaction of the receiving antenna on the source is negligible.

In order to aid the simplicity of formulation, the equations given are for the orientation of source and receiver for which the maximum signal is received.

a. Pickup from an Electric Dipole

The field of an elementary electric dipole is given by the three vectors[3,4]:

$$E_R = \frac{2Pe^{+j\omega t}}{4\pi\varepsilon_0}\left(\frac{1}{R^3} + \frac{jk}{R^2}\right) \cos\theta \cos kR$$

$$E_\theta = \frac{Pe^{+j\omega t}}{4\pi\varepsilon_0}\left(\frac{1}{R^3} + \frac{jk}{R^2} - \frac{k^2}{R}\right) \sin\theta \cos kR$$

$$H_\phi = \frac{j\omega Pe^{+j\omega t}}{4\pi}\left(\frac{1}{R^2} + \frac{jk}{R}\right) \sin\theta \cos kR$$

where P is the dipole moment, $\omega = 2\pi$ times the frequency, ε_0 is the permittivity of free space $= 8.854 \times 10^{-12}$ farads per meter, R and θ are given by Fig. 6, and k is the propagation constant,

$$k = \frac{\omega}{c} = \frac{2\pi}{\lambda}$$

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where c is the velocity of electromagnetic waves = 3 x 10^8 meters per second, and λ is the wavelength of a plane wave.

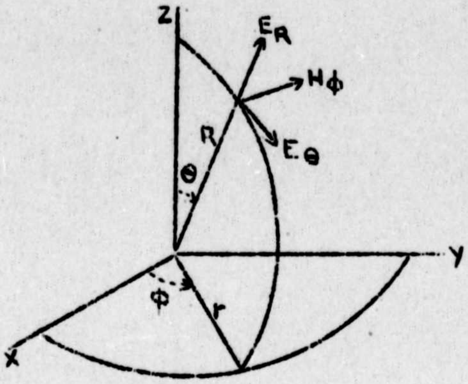

Fig. 6

The voltage picked up by a coil is given as before, by

$$V_{EH} = 2.5 \times 10^{-5} f R_0^2 NH$$

assuming H is uniform throughout the loop and equal to the magnitude at the center of the loop which is at a distance R from the dipole.

The voltage induced in a dipole antenna short compared with 0.3λ is given as in the previous section by

$$V_{EE} = \frac{LE}{2}$$

where E is the component of the electric field intensity parallel to the antenna.

Of interest is the ratio of V_{EE} to V_{EH} for the same distance R. For distances which $kR < 1$, it is only necessary to consider the contribution of the first terms in the expressions for E_θ and H_ϕ. These terms will predominate for positions perpendicular to the axis of the dipole source. The value of E along the receiving dipole will remain substantially constant at the value of E_θ at its center point providing the separation of source and receiver is equal to or greater than L. It is noted that the first term in E_R makes a larger contribution than E_θ along the axis of the receiving dipole but here the magnetic field will be zero. With these approximations employed the ratio of V_{EE} to V_{EH} becomes

$$\frac{V_{EE}}{V_{EH}} = \frac{3.60 \times 10^{+14}\, lL}{NRf^2 R_0^2}$$

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For a sample computation f = 20 megacycles, L = 1 meter, N = 10 turns, R_0 = 0.15 meters and R = 1 meter, then

$$\left|\frac{V_{EE}}{V_{EH}}\right| = \left| j \frac{3.60 \times 10^{14}}{10 \times (2 \times 10^7)^2 \times (0.15)^2} \right| = 4$$

At lower frequencies the ratio is higher unless the number of turns of the loop is increased considerably. Of course, this computation does not take into account the coupling or tuning in the input of the receiver, which may be to the advantage of either the coil or the rod, depending on the physical setup. Because of the difficulty in designing coils of many turns, the pickup of a coil at a given distance will generally be less than that of a rod, providing the source is an electric dipole.

b. Pickup from a Magnetic Dipole

The field of an elementary dipole is given by (3,4)

$$H_R = \frac{2me^{+j\omega t}}{4\pi} \left(\frac{1}{R^3} + \frac{jk}{R^2}\right) \cos\theta \cos kR$$

$$H_\theta = \frac{me^{+j\omega t}}{4\pi} \left(\frac{1}{R^3} + \frac{jk}{R^2} - \frac{k^2}{R}\right) \sin\theta \cos kR$$

$$E_\phi = \frac{-j\omega\mu_0 \, me^{+j\omega t}}{4\pi} \left(\frac{1}{R^2} + \frac{jk}{R}\right) \sin\theta \cos kR$$

where m is the dipole moment and μ_0 is the permeability of free space = 1.257×10^{-7} henries per meter.

Employing the same formulas as used for the electric dipole and making the same approximations for the electric field as were made for the magnetic field and vice versa, the ratio of V_{HE} to V_{HH} becomes

$$\frac{V_{HE}}{V_{HH}} = j \frac{0.158 \, LR}{NR_0^2}$$

Using the same quantities which were used in the calculation of the electric dipole:

$$\left|\frac{V_{HE}}{V_{HH}}\right| = \left| j \frac{0.158}{10 \, (0.15)^2} \right| = 0.7$$

An expression which does not depend implicitly on the frequency. However, the number of turns of the coil will decrease as frequency increases so that this ratio will decrease for lower frequencies, an effect which is the inverse of the ratio V_{EE}/V_{EH}.

Except for very high frequencies, the ratio will generally be lower for this case than for the electric dipole.

For comparison purposes, we can also compute the ratio of V_E to V_H at a great distance ($R >> \lambda/2\pi$). The ratio is the same regardless of whether the source is electric or magnetic and is

$$\frac{V_E}{V_H} = - \frac{7.52 \times 10^6 L}{N f R_o^2}$$

If the same values are used as were previously employed, this becomes

$$\left|\frac{V_E}{V_H}\right| = \left| - \frac{7.52 \times 10^6}{10 \times 20 \times 10^6 \times (0.15)^2} \right| = 1.67$$

APPENDIX B.

Frequency Conversion

The users of several existing types of noise meters have observed certain anomalous effects. Some of these are:

1. Two noise meters whose sine wave calibrations are identical give different indications when reading the same noise.

2. When reading random noise, a noise meter may give different indications at different frequencies even though both the sine wave calibration of the noise meter and the output of the source are constant with frequency. Two noise readings at the same frequency but on overlapping portions of adjacent frequency bands of the same meter also may disagree.

It has been suggested that the mixer may cause these effects. Because the mixer is a non-linear device, it was thought that the response to a broad band of frequencies may somehow differ from single frequency response; that spurious responses and intermodulation products might cause the unexplained discrepancies between noise and sine wave readings.

The reception of speech and music with superheterodyne receivers is cited as an example of the linearity (distortionless reproduction of the envelope) of mixers at broadcast frequencies with limited types of transient multi-frequency inputs. The conventional noise meter responds only to amplitude modulation. Assuming that the noise over a narrow band can be represented by a single frequency wave with amplitude and phase modulation, two differences between the noise and the amplitude modulated broadcast signals are:

1. The percentage modulation by the noise may be greater than 100 percent, whereas for broadcast transmission it is kept below this figure by F.C.C. regulation.

2. The broadcast signal is not phase modulated.

So far, preliminary investigation has not shown how either of these differences could cause the previously listed effects.

Intermodulation

To determine the possible intermodulation products, the non-linear action of the mixor was analyzed. That analysis has been performed in the literature in two different ways. One method uses Fourier Series (6), while the other (7) uses a power series based upon Taylor's Theorem. Each method has certain advantages. However, since it is possible to write down the frequencies which appear in the plate current of a mixer with more generality when using the power series method, that method was used. The input to the mixer was taken to be a signal voltage at the frequency to which the noise meter was tuned, an interfering voltage at any other frequency, and the local oscillator voltage. Terms up to and including the third order were considered.

The analysis shows that there are quite a few frequencies at which interference may occur. Most of them may be eliminated upon inspection because they obviously never can fall in the pass band of the IF channel. One possible source of interference is image frequency response. This effect may be eliminated by proper design of the RF circuits. If the gain of the RF stage at that frequency is 40 db below the gain at the center of the pass band, then it is very unlikely that image response will be troublesome. There is further the response due to oscillator harmonics. These too may be kept down by proper RF selectivity.

Experimental Verification

Using a Hallicrafter SX-28A Radio Receiver, two tests were made.

1. The receiver tuning was fixed and a signal of variable frequency applied to the input.

2. A signal fixed at the frequency to which the receiver was tuned was applied at the input, in series with a stronger signal whose frequency was varied.

When the variable frequency was outside the pass band of the receiver no interaction effects between the two signals were noted. The only responses noted were those at the image frequencies and those due to the local oscillator harmonic frequencies. When the variable frequency was within the pass band, the two frequencies added in a manner predicted by the theory of linear addition of two sine waves.

The Mixer as a Circuit Element

The theory that the anomalous effects previously noted are caused by some change in the input impedance of the convertor has been advanced. In general, the input impedance of multigrid mixers depends upon [5,8]:

1. Tube type
2. Type of mixer
3. Operating point and frequency
4. External circuit.

The following effects have been noted in the literature. Some are as applicable to RF and IF amplifiers as to mixers:

1. Capacitance between grid and ground. This should not cause any difficulty on sine wave measurements or any difference between sine wave and noise measurements.
2. Reflected capacitance and conductance due to grid to plate capacitance and amplification of the tube, known as the Miller effect. Detuning due to changes in AVC voltage also comes under this heading. While these effects may cause discrepancies in the readings of existing noise meters, they probably can be made negligible by proper design.
3. Input conductance due to:
    a. Grid cathode capacitance and inductance in the cathode circuit.
    b. Leakage and hysteresis in the tube insulating material.
    c. Transit time.

    The input conductance due to these three effects is usually lumped together and given by:

    $$g_1 = K_c f + K_h f^2$$

    An average value of K_c is 0.3 micromhos/mc for octal base tubes without grid cap. Some typical values of K_h at average tube operating conditions a

K_h = - 0.05 micromhos/mc^2 (Type 6A8)

K_h = + 0.005 " " (" 954)

K_h = + 0.15 " " (" 6L7)

K_h = + 0.05 " " (" 6SJ7)

4. A current of local oscillator frequency which flows to the signal grid because of space charge coupling to the local oscillator grid.

5. Distortion due to overload or cut-off.

It can be seen how these effects, especially 2., 3., 4. and 5. could cause differences between noise meters or changes with frequency in the same noise meter. However, it is not evident at present how any of these effects, with the possible exception of transit time and distortion, could cause two noise meters whose sine wave characteristics are identical to disagree on noise. Since most of the noise meters operate at frequencies where transit time is negligible, it seems that the overload effect is most likely to cause trouble.

APPENDIX C.

Detectors of Electrical Noise

Definition of Detection

For the purpose of noise measurement, detection will be defined as the process of converting some characteristic of the electrical noise energy (at radio or intermediate frequencies) into a form suitable for quantitative measurement by an indicating device.

Measurable Quantities

There is no assurance at this date that the measurement of the peak, r.m.s., or average value of a noise voltage will give its interfering effect. In fact, the situation is so complicated that it may be necessary to measure more than one of these quantities, or to measure some other characteristic of noise.

Best Methods for the Measurement of Peak, Average and R.M.S.

The following recommendations are based upon the measurement of a periodic signal. Naturally, the choice depends upon the specific application involved, and will be a compromise on many factors.

a. Peak

1. The most truly peak reading device is the Cathode Ray Tube (following an i.f. stage), but it is difficult to read noise peaks on it.

2. Slideback circuits are truly peak reading for large values of signal, but they require a manual adjustment for each reading.

3. For ease of measurement, a diode circuit is probably the best, but the readings are affected by both meter and electrical time constants.

b. Average

The plate or anode bend rectifier is recommended for its high input impedance and small dependence of the metering circuit upon the preceding stage.

c. R.M.S.

1. The full-wave square-law triode is preferred for moderate i.f. (or r.f.) frequencies since it measures the r.m.s. value of an asymmetrical wave. Its use is limited to low level work.

2. For very high frequencies, the thermistor and the thermocouple instruments may be useful. However, the characteristics of both devices are subject to change with temperature. In addition, the thermocouple has a small overload rating and a low input resistance.

At this time, the methods mentioned above are the most promising for measurements of peak, average, and r.m.s.; but it is possible that a specific application may dictate the use of some other method.

Logarithmic Response

The use of a logarithmic response is an obvious aid in the measurement of widely varying amplitudes which are characteristic of some types of noise. Four known devices accomplish this result as follows:

1. An indicating meter using specially shaped pole pieces.

2. A logarithmic d.c. amplifier between the detector and a linear indicating device.

3. Logarithmic i.f. stages using the exponential characteristics of variable-mu tubes in a special circuit.+

4. Automatic-gain-controlled i.f. stages using variable-mu tubes.

+) Refer to page 8 of "A Comparison of Detectors for Electrical Noise", an informal memorandum on Project PB, University of Pennsylvania, dated September 21, 1945.

The first device may be used in circuits for reading peak, average or r.m.s. where the currents produced by the detector are respectively proportional to the peak, average, and square of the applied voltage.

The second device may be used in circuits for reading peak, average and r.m.s. where the currents produced by the detector are respectively proportional to the peak, average, and average of the square of the applied voltage.

The third arrangement may be used in circuits for reading peak and average where the detector itself reads respectively the peak and average of the voltage applied to it. In the case of a detector whose response is itself proportional to the mean square of the applied voltage, the application of this i.f. circuit results in a reading which is proportional to the mean square value of the logarithm of the voltage applied to the i.f. input, not to the logarithm of the mean square or r.m.s. values as would be desired.

The fourth device performs in the same manner as the third when the a.g.c. time constants of the former are long compared with the intervals between successive pulses. Although no analysis has been made for the case when this is not true, the response is then probably a complicated function of the input voltage wave-form. Some commercial radio noise meters have been produced with a.g.c. controlled i.f. stages, but there has been considerable discussion about the effect of the a.g.c. time constant when a reading due to noise is taken.

<u>Methods for the Measurement of Other Characteristics</u>

Other characteristics which may be particularly valuable for "spike" type noise, are the following:

a. Pulse repetition frequency.

b. Pulse rise time or decay time, or both.

c. Pulse duration.

d. Interval between successive pulses.

e. Number of pulses above a given value per unit time.

The measurement of an averaged pulse repetition frequency can be made by any one of a number of counting circuits operated over a given time interval. Items (b), (c) and (d) involve the measurement of relatively short time intervals. Many time and speed meters have been devised, but nearly all of them depend upon using tubes to control the charging or the discharging of a condenser. They read the change in condenser voltage, which is proportional to the elapsed time. Time measurements can also be made by comparing the unknown time with the known time between standard pulses on a cathode ray tube screen. Method (e) involves the use of both counting and timing circuits.

The methods considered here are not intended to be all-inclusive. As work progresses, methods for the measurement of other characteristics showing promise will be considered.

Response of the Diode to Random Noise

We have not investigated the response of the diode to random noise. However, excellent articles on this subject are available [9,10,11].

APPENDIX D.

Calibration of the Noise Meter

In order to complete the specifications for the design of a noise meter, a method of calibrating the device is required.

In general this calibration may be performed by feeding a signal of known amplitude and wave form into the meter and determining the meter's response as a function of frequency. The exact type of signal used will depend upon many factors such as complexity of circuit, ease of adjustment, and stability of the signal generator. A further requirement is that it should have the character of noise itself since it is quite possible that with circuits that may be used, responses to various types of signals will be different. It is not the purpose of this section to discuss which type signal should be used since insufficient data is now available on the character of noise and noise meter circuits. The succeeding paragraphs give an outline of various generators which might be used. Evaluation of each is based only on simplicity, stability, frequency range, size, and weight.

Sine Wave Sources

These have a fair stability. Their size and weight will depend upon the frequency range desired. Either a calibrated output meter or a well stabilized circuit is required and maintenance is likely to be a problem in the field.

Random Noise Sources

The best of the random noise sources seems to be the temperature limited or shot diode [12]. If tungsten filaments and highly evacuated tubes are used, the stability is good. The circuit is a simple one-tube affair. The size and weight are both very small.

The output is usable up to 300 mc. The frequency range is limited by transit time and the internal L and C of the diode. It is not necessary to calibrate the shot diode, the output being proportional to the d.c. component of the plate current. The output is small but within a reasonably wide frequency bandwidth, with a typical load impedance, it is more than five times the thermal noise and tube noise of the first stage. This is sufficient for calibration purposes.

Spike Noise Sources

On a theoretical basis the spike noise source(13) with the most extended frequency range is the Purdue charged transmission line. The frequency range extends to 400 mc. It is to be emphasized that these results are theoretical and have not been checked experimentally. This source is intermediate between the shot diode and the sine wave source in size and weight. The source at present is unsatisfactory due to an instability caused by the contacts. There are several other spike noise sources available such as the Detroit Signal Laboratory's thyratron pulse generator(14) and Harvard's "blocking oscillator" pulse generator. Their frequency range is less than that of the Purdue source being usable approximately to 50 mc. Both sources are stable; the Harvard one being the better in this respect. The size and weight of these two sources are smaller than the Purdue source. The outputs of all the sources are sufficient to calibrate the noise meter below 50 megacycles.

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Progress is reported of investigations of radio interference phenomena including the development of standards for measurements and measurement technique, comparison of various types of noise meters, and construction of a standard noise meter. A critical analysis was made of present noise meter circuits and their responses to various types of noise. In addition, studies were made to establish specifications for noise meter performance. Various instruments, calibrated with sine wave signals, read differently (as much as 1000 to 1) when they were presumably reading the field intensity from the same noise source. Antennas for noise meters, frequency conversion, noise detectors, calibration of the noise meter, and methods of coupling a noise meter to a source of a noise are discussed.

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